Superconductivity-Man: An Electro-Magneto fusion or an electromagnetic delusion?

***Introduction*— With the recent release on the silver screen of *Spiderman: No Way Home* and the return of the longstanding villain Electro, it has personally inspired thoughts of the real-life potential for supervillainy and how the next mad scientist (aren't we all after these past two years) could best channel their expertise for electromagnetic evil.**

60 years after Electro and Magneto were first introduced in the Marvel comics, in a lot of areas what was once considered science fiction has now become reality and so it poses the question on the extent that it applies to the classic supervillains.

I. Introduction

WITHOUT mutant X-genes, superpower granting lightning strikes or a vat of electric eels to fall into (though their method of generating electricity is admittedly an interesting dive), to stay grounded in reality our supervillain must instead have an external source of power.

Here lies the basis of Superconductivity-Man, a villain with a name that is fairly self-explanatory in the source of his capabilities, though slightly lacking in creativity (suggestions are welcome).

A. *The Backstory*

Every supervillain needs a backstory and ours is a bit of a slow burn of over a century and one that is still being written. The origins of superconductivity date back to 1911, initially stumbled upon by a student of H.K. Honnes during low temperature experiments inspecting the electrical resistance of Mercury.

It was found that upon being cooled to a critical temperature (roughly 4K) the resistance of Mercury was seen to drop by a factor of about 20,000x, essentially vanishing [1]. The experimental results can be seen in Fig.1.

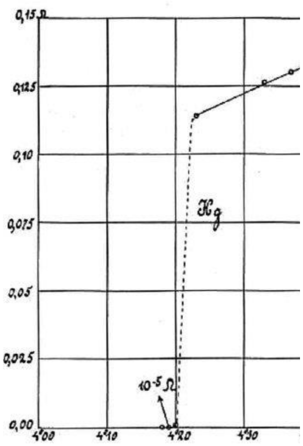

Fig.1. Plot of H.K. Honnes 1911 experimental results for resistance vs temperature of Mercury

The understanding of their findings came 22 years later in 1933 from Meissner and Ochsenfeld's studies and their discovery of what became known as the Meissner effect. Similar to the earlier studies, when certain materials (later defined as superconductors) were cooled below a threshold temperature, even when subjected to an external magnetic field their internal field was found to be zero. The divergence from the classical model and superconductivity's quantum nature was first highlighted by these findings.

In the classical model of a perfect conductor, if cooled below critical temperature T_c then subjected to an external field $\boldsymbol{B}$, the internal field remain 0 throughout due to induced circulating current inside the conductor (this current disappears as $\boldsymbol{B}$ is removed with internal field remaining 0). However, if already subject to field $\boldsymbol{B}$ and then cooled the internal field does not change, if $\boldsymbol{B}$ is then removed a permanent (due to 0 resistance) circulating current is induced and a permanent $\boldsymbol{B}$ field remains.

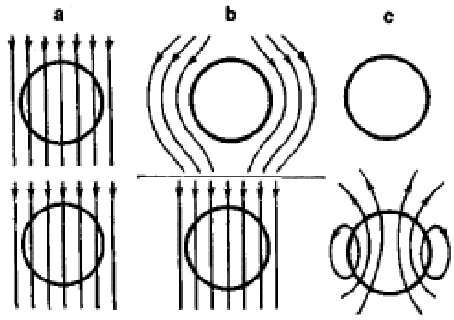

Fig.2. Field line diagram for a superconductor (top) vs a perfect conductor (bottom) when (a) an external magnetic field is applied (b) the material then being cooled below T_c and (c) the external field being removed (Columbia University Press 2013)

A mathematical model soon followed with the London equations in 1935 [3], describing the behaviour that was seen using the second of the two equations and Ampere's law,

$$\nabla \times \boldsymbol{j} = -\frac{n\mathrm{e}^2}{m}\boldsymbol{B} \qquad \text{and} \qquad \nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{j} \tag{1}$$

finding the solution to the 2nd order ODE formed and giving the magnitude of the field B at depth z below the surface

$$B = B_0 e^{-\frac{z}{\lambda}} \qquad \text{where} \qquad \lambda = \sqrt{\frac{m}{\mu_0 n e^2}} \tag{2}$$

This equation showed that when at sufficient distance below the surface (the penetration or London depth ~10-100Å) the magnitude is approximately zero, supporting the experimental findings.

II. Making Superconductivity-Man Super

Now for the more interesting part, what can our potential supervillain actually do by harnessing the powers of superconductivity?

A. *Non-Existence of Resistance*

On the most basic end, if Superconductivity-Man's powers are to be electromagnetic in nature they must be electrically powered. Any power source and circuitry to support this must therefore be as efficient as possible, not only for storage considerations but also for our villain to be protected from his own electrical powers his super-suit must act as a wearable Faraday cage, otherwise any resistance in the wiring would leave him cooked like a rotisserie chicken.

Luckily, one of the first properties of superconductors that was found was its lack of resistance, but how and why does this happen? After the Meissner effect and the quantum nature of superconductivity was observed, many approaches were taken to explain the behaviour and in the 1950s both the Ginzburg-Landau and Bardeen-Cooper-Schrieffer (BCS) theories were proposed.

1) *Ginzburg-Landau Theory*

The Ginzburg-Landau theory took a mathematical approach to the problem, treating it as a quantum phenomenon and proposing a mathematical model.

The theory built upon L. Landau's prior work and theory of continuous phase transitions of a material [4], applying it to the transition to the superconducting phase and analysing the change in its free energy.

The free energy F of the superconductor near T_c was expressed in terms of a complex order parameter ϕ that had the form of a wavefunction $\varphi(\boldsymbol{r}) = |\varphi|e^{i\phi(\boldsymbol{r})}$ with $|\varphi|^2$ representing a density [5]. In the case of the Ginzburg-Landau theory, the density gives the proportion of electrons in the superconductor that have become superfluid.

The free energy F is given by

$$F = F_n + \alpha|\varphi|^2 + \frac{\beta}{2}|\varphi|^4 + \frac{1}{2m^*}|(-i\hbar\nabla - 2\mathrm{e}\,\boldsymbol{A})\varphi|^2 + \frac{|\boldsymbol{B}|^2}{2\mu_0} \quad (3)$$

where F_n is the free energy in the non-superconducting phase, α and β are treated as parameters of the phenomenon, $m*$ is effective mass and $\boldsymbol{B} = \nabla \times \boldsymbol{A}$. When F is minimised with respect to ϕ and $\boldsymbol{A}$ you get the two Ginzburg-Landau equations

$$\alpha\varphi + \beta|\varphi|^2\varphi + \frac{1}{2m^*}(-i\hbar\nabla - 2\mathrm{e}\boldsymbol{A})^2\varphi = 0 \quad (4)$$

$$\boldsymbol{j} = -\frac{\mathrm{e}}{m^*}(i\hbar(\varphi^*\nabla\varphi - \varphi\nabla\varphi^*) + 4\mathrm{e}\boldsymbol{A}|\varphi|^2) \quad (5)$$

These equations gave rise to two properties of a superconductor, the previously seen penetration depth λ given in terms of the Ginzburg Landau model

$$\lambda = \sqrt{\frac{m^*\beta}{4\mu_0 \mathrm{e}^2|\alpha|}} = \sqrt{\frac{m^*}{4\mu_0 \mathrm{e}^2\varphi_0^2}} \quad (6)$$

where φ_0 is the equilibrium value of the superfluid electrons. When displaced from this equilibrium, the exponential law of its recovery is determined by its coherence length ξ,

$$\xi = \sqrt{\frac{\hbar^2}{4m^*|\alpha|}} \quad (7)$$

These two properties are governed by the material of the superconductor itself and in finding these it was first seen that superconductors could be split into two separate categories, something we will return to later.

2) *Bardeen-Cooper-Schrieffer (BCS) Theory*

The BCS theory on the other hand took a much more physical look at the situation. The BCS theory combined the work of J. Bardeen, who was studying the aforementioned coherence length, with the research of L. Cooper into the behaviour of pairs of electrons near T_c [6]. Alongside R. Schrieffer the trio published the *Microscopic theory of superconductivity* [7] in 1957, further adding to it reproducing the works of W. Meissner, V. Ginzburg and L. Landau later in the *Theory of superconductivity* [8].

Previously, it had been proposed that a material would display superconductive properties when electrons in the material had an energy gap between the ground and first excited state of $\sim kT_c$. L. Cooper proposed the energy gap arose due to the formation of Cooper pairs within the material allowing the electrons to condense into a superfluid ground state.

Cooper pairs are said to be formed when a pair of electrons enters into a bound state due to an attraction [6]. Usually, due to the Pauli exclusion principle, fermions (particles with non-integer spin) are unable to occupy the same quantum state. However, once bound due to the resultant Cooper pair having a total integer spin it forms and acts as a composite boson.

The Cooper pairs can all thus condense into the same ground state that, unlike in a typical conductor, no longer had a continuous set of allowed energy states instead having the proposed energy gap leading to the material's superconductive properties. The theory became the first major connection between superconductivity and quantum physics, previously it had been presumed but the BCS theory served to truly link the two.

Although Cooper pairs are a result of quantum behaviour, it can be useful to explain using a classical and physical model instead.

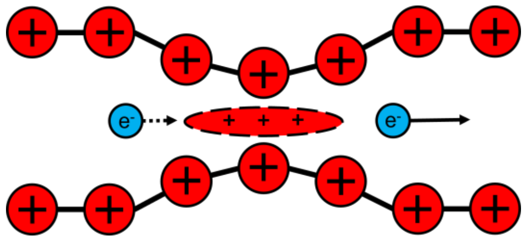

Fig.3. Diagram of simple classical explanation for Cooper pairs, electrons shown in blue and ions in lattice shown in red

As the first electron on the right passes through the lattice shown in Fig.3., the lattice becomes distorted due to the attraction with positive ions. Due to the deformations in the lattice, an area of positive charge density is formed thus attracting the electron on the left. This attraction is sufficient to overcome the electrons' Coulombic repulsion and in turn, supply the attractive force necessary to form a Cooper pair.

More specifically in the quantum interpretation, this is due to electron-phonon interactions where the electrons interact with the phonons (quantised vibrational waves) produced due to the vibration in the lattice caused by the first electron, later being shown to be the reason for materials with heavier lattices having a lower threshold temperature.

3) *Applications*

One area the zero resistance would be especially useful is in the battery powering Superconductivity-Man's powers.

Powering such a suit would require a large quantity of energy and this requires taking certain liberties with assumptions over the capabilities of fusion power. Assuming we are able to harness the power of fusion and condense it to a core similar to that of Tony Stark's, superconductors must play a critical part.

A number of tokamak fusion reactors are in development across the world and a large number of them rely upon superconductive materials [9]. Besides the obvious point of no resistance meaning no energy dissipation in the form of heat, superconductors are especially important in fusion reactors as the fuel must be kept in a plasma state and a magnetic field acts to confine it. The stronger the magnetic field used, the greater the temperature and pressure the fuel can be held at, leading to the fusion power produced in the tokamak being proportional to $|\boldsymbol{B}|^4$.

To produce the strongest magnetic field possible, superconducting magnets are used as they can conduct much greater electric current than their non-superconducting counterparts, thus allowing for a much stronger field.

However, they do come with the drawback of needing to be cooled (whether with a coolant ie. liquid helium or mechanically through refrigeration). Superconducting magnets can also be found in widespread use in equipment such as MRI machines, spectrometers, and more notably in particle accelerators such as the Large Hadron Collider.

B. *Designing the super-suit*

Every good supervillain needs a super-suit and to make a good super-suit, the properties required of it must be considered. In the case of superconductors, the material the superconductor consists of determines its properties.

As mentioned previously the Ginzburg-Landau theory [5] predicted the split of superconductors into two distinct types. The theory found that materials could be separated in behaviour by the ratio of their penetration depth to their coherence length, the Ginzburg-Landau parameter $\kappa = \lambda/\xi$.

The relative nature of a superconductor can be quickly determined using κ with the two types being divided by their values: Type I superconductors having a value of $0 < \kappa < 1/\sqrt{2}$ and Type II superconductors a value of $\kappa > 1/\sqrt{2}$.

1) *Type I*

Type I superconductors behave typically with the properties and phenomena that have been previously mentioned. When cooled below a certain threshold temperature, they fully undergo the Meissner effect with all magnetic field being expelled from the material, seen with the value of κ showing a relatively smaller penetration depth.

However, they are also easily disrupted by external magnetic fields for this reason, being known as soft superconductors and having limited technical application. Type I superconductors are typically mono-elemental, eg. Aluminium and Zinc, besides two exceptions: the alloy of $TaSi_2$ and the covalent superconductor SiC:B.

2) *Type II*

Type II superconductors are more complicated having two distinct superconductive phases. Below their lower critical field strength B_{c1}, Type II superconductors behave the same as their Type I counterparts expelling almost all external magnetic field below the critical temperature.

However, at stronger fields but still below their upper critical field strength $B_{c1} < B < B_{c2}$ the material exists in a mixed phase. While in the mixed phase, some magnetic field penetrates the material leading to circulating eddy currents shielding the rest of the material from the field.

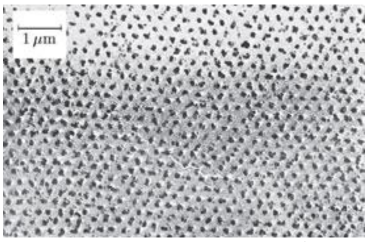

Fig.4. Type II superconductor with magnetic field perpendicular to surface showing the eddy currents (dark spots) and superconducting region (light) (Open University, 2012)

Type II superconductors are typically metal alloys, however unlike most elemental superconductors Niobium, Vanadium and Technetium are also Type II. Type II superconductors are the only high temperature superconductors with ceramic cuprate-perovskite based materials achieving the highest critical temperatures, some with $T_c > 77K$, the boiling point of liquid nitrogen.

C. *Is it a bird? Is it a plane?*

Of course, besides being electrically powered, what must Superconductivity-Man be able to do? Fly! Well… at least levitate, and wouldn't you be pleased to hear that's also a phenomenon associated with superconductivity.

Type II superconducting materials can levitate above a magnet through two separate mechanisms, the previously mentioned Meissner effect and a phenomenon known as quantum locking or magnetic flux pinning.

1) *The Meissner effect*

Quantum levitation can be caused purely by the Meissner effect in Type I superconductors [10]. As seen before, when a Type I superconductor is below threshold temperature it expels all magnetic field. When exposed to an external magnetic field, the opposing induced field inside the superconductor polarises the material. This polarisation is in the opposite direction to that of the magnet inducing it and so causes a repulsive force between the two objects. The superconductor is thus held in equilibrium above the magnet and levitates.

However, the uses for this form of quantum levitation are limited. Not only do Type I superconductors come with their associated downsides but also the equilibrium the material is held in is unstable, if not contained the superconductor can easily float off of the magnet.

2) *Quantum Locking*

The more interesting case of quantum levitation is that caused by quantum locking/flux pinning [11]. Due to the nature of Type II superconductors allowing some magnetic field penetration, if a superconductor is cooled to below its threshold temperature in the presence of a magnet, some of the field penetrating the material becomes 'locked' in place. This phenomenon can also be seen for sufficiently thin Type I superconductors where the penetration depth is comparable to its thickness. The amount of magnetic flux is quantised in the form of flux tubes passing through the material, any movement of these flux tubes trapped in the material is resisted and thus the superconductor is held in space.

3) *Applications*

Flux pinning is much more stable as it doesn't rely on the repulsive equilibrium versus gravity and so has many more potential uses. One of these uses is in the MagLev trains in operation in Japan, China and South Korea, harnessing magnetic levitation [12] to float above the rails due to repulsion between electromagnets on the train from those on the tracks.

Because of the lack of friction between the train and the tracks, MagLev trains are the fastest in operation with commercial speeds of up to 505km/h (and a fastest recorded speed of 574.8km/h) while also being more energy efficient, safer and more sustainable in comparison to standard trains.

The train holding both of the previous records is the SCMagLev [13] (currently in development for commercial operation starting in 2027) which makes use of superconducting electromagnets to propel the train while reportedly consuming 30% less energy. Research is also being done to utilise the quantum locking phenomena.

III. Conclusion

Despite being an exciting and ongoing area of research with widespread and important future applications, one of those applications is unfortunately not making Superconductivity-Man super. Even with a futuristic Tony Stark style arc reactor powering the suit, the plans for villainy fall flat across a number of hurdles.

Whether it is the vast amount of coolant required to maintain sub-critical temperatures, the levitation limited to hovering a short distance from the floor or the reliance on external magnets, it just seems that superconductivity is not particularly suited to general villainy.

Maybe our mad scientist would be better off channeling his time and effort into the multitude of other options instead.

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Original Plan

Superconductivity and Bose-Einstein Condensates

Introduction

- Brief introduction on superconductivity and bose-einstein condensates
    - Why are they important?
- Overview of history
- Overview of future and uses

Superconductivity

- Short explanation
- History
    - H K Onnes 1911
    - Meissner and Ochsenfeld 1933
    - Ginzburg-Landau 1950 and Bardeen-Cooper-Schrieffer 1957 theories
- Meissner effect
    - Quantisation of magnetic flux/permanent currents
- Types of superconductor
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- Thermodynamic phase
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    - Cooper pairs and superfluidity
- BCS and high temperature superconductivitiy
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Bose-Einstein Condensates

- Brief explanation
- History
    - Bose Gas and Bose-Einstein statistics
    - Bosons
- Superfluidity
    - Transition from BCS to BEC
- Observations and Properties of BEC
    - What makes them different?

Summary and the Future

- Importance in current day
- Ongoing research
- Possible future applications

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[1] J Bardeen, L Cooper, J. R. Schriffer. "*Theory of Superconductivity,*" *Physical Review*, Dec, 1957
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Alterations and Developments

It soon became clear that the original scope of the article was much too broad if I intended to delve into the topics with any depth and so decided to narrow down the focus considerably.

Deciding on a more novel approach also lead to the structure being altered and the framing of topics hopefully portrayed in a more engaging manner.